Summary of studies of the η meson production with polarized proton beam at COSY-11

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Abstract. We report on the COSY-11 measurements of the analysing power for the $\vec{p}p \to pp\eta$ reaction and interpret the results in the framework of the meson exchange models.

Keywords: η meson production, production mechanism, analysing power
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MOTIVATION

In recent years the processes of the meson production have been extensively studied in the context of understanding the strong interaction, responsible for the existence of hadrons. The growth of the database of the observables connected with the meson production in the hadronic collisions made possible the verification of the predictions of the effective theories.

A particular interest has been put on the studies of the properties of the η meson [1, 2]. Despite the fact that the discovery of this meson took place over forty years ago [3] its production mechanism still remains unknown. Understanding of the production process of the η meson may allow the theoretical models to be revisited with new input parameters: the coupling constants in the description of the production process of the η meson, the initial and final state interactions and also dimensions of the reaction region.

From precise measurements of the total cross sections of the η meson production in the $pp \to pp\eta$ reaction [4, 5, 6, 7, 8, 9, 10, 11] it was concluded [12, 13, 14, 15, 16, 17, 18, 19] that this process proceeds through the excitation of one of the protons to the $S_{11}(1535)$ state which subsequently deexcites via the emission of the η meson (see Fig. 1). In practice, within the meson exchange picture, the excitation of the intermediate

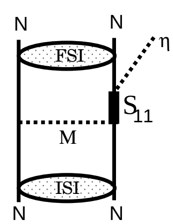

FIGURE 1. The mechanism of the η meson production in nucleon-nucleon collisions. M denotes an intermediate pseudoscalar or vector meson, e.g. π, η, ω, ρ. ISI and FSI indicate initial and final state interaction between the nucleons.

resonance can be induced by exchange of any of the pseudoscalar or vector ground state mesons between the nucleons [20, 21, 22]. Based on the excitation function only

it was, however, impossible to disentangle the contributions to the production process originating from the π, η, ω or ρ meson exchange.
More constraints to theoretical models [12, 13, 14, 15, 16, 17, 18, 19] have been deduced from the measurement of the isospin dependence of the total cross section by the WASA/PROMICE collaboration [23] [1]. The comparison of the η meson production in proton-proton and proton-neutron collisions revealed that the η meson is by a factor of twelve more copiously produced when the total isospin of the nucleons is zero with respect to the case when it equals to one. As a consequence an isovector meson exchange is strongly favoured as being responsible for such a strong isospin dependence. This result was already a large step forward but still the relative contributions of the ρ and π mesons remained to be established. For this purpose we have determined the analysing power for the $\vec{p}p \to pp\eta$ reaction since its theoretical value [18, 19] is sensitive to the assumption on the type of exchanged meson.

The first test measurement of the analysing power for the $\vec{p}p \to pp\eta$ reaction at the excess energy of Q = 40 MeV has been performed by the COSY-11 collaboration in the year 2001. The method of the analysis and the results have been reported in [28]. Unfortunately, the data from this tentative measurement are bared with rather large error bars, and at the level of accuracy obtained in this experiment no constructive statement could have been done in order to distinguish between two different hypotheses of the η meson production. Similarly, the intepratation of the data obtained by the DISTO collaboration [29], performed in the far-from-threshold region at the excess energies of Q = 324, 412, and 554 MeV suffered from the lack of a theoretical prediction for the analysing power. This is due to the fact that far from the reaction threshold the higher partial waves are involved in the reaction process, making the theoretical description complicated.

Further investigations were necessary and two additional experiments devoted to the determination of the analysing power for the $\vec{p}p \to pp\eta$ reaction in the close-to-threshold region have been performed by the COSY-11 collaboration. In this paper we shall briefly present the experimental method and summarize results from these two measurements. For the details of the analysis the interested reader is referred to the reference [30].

METHOD OF MEASUREMENT

Experiments have been performed utilizing the COSY-11 facility [31, 32, 33] at the COoler SYnchrotron and storage ring COSY [34] in the Research Center Jülich, Germany. The analysing powers have been measured during two runs at different beam momenta: p_{beam} = 2.010 GeV/c (May 2003) and 2.085 GeV/c (September 2002), which for the $\vec{p}p \to pp\eta$ reaction correspond to the excess energies of Q = 10 and 36 MeV, respectively.

COSY-11 detection setup is described in [31]. A vertically polarised proton beam [35]

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[1] The measurement of the isospin dependence is being extended by the COSY-11 collaboration [24, 25, 26] to the η' production which may also be sensitive to gluonic production mechanism [27].

had been stored and accelerated in the COSY ring. The target [36] is installed in front of the accelerator's dipole magnet acting as a momentum separator for the charged reaction products. The positively charged ejectiles are registered in drift chambers and scintillator hodoscopes. For each particle its direction of motion and time of flight on a nine meter distance was measured. Tracking back these trajectories through the known magnetic field inside the dipole magnet to the reaction vertex allows for the momentum reconstruction. Independent determination of momentum and velocity from the time-of-flight measurement permitted the identification of the charged particles. The η meson has been identified on the basis of a missing mass technique.

For the determination of the analysing power of the η meson at a given value of the polar angle θ_η and the azimuthal angle ϕ_η one has to measure a left-right asymmetry of the yields of the η meson production. The process of production is considered in the so called *Madison coordinate frame* [37], which in our case has its y axis parallel to the $\vec{p}_{beam} \times \vec{p}_\eta$ vector, with $\vec{p}_{beam}$ and $\vec{p}_\eta$ denoting the momentum vectors of the proton beam and the η meson in the center-of-mass system, respectively. The z axis of the Madison coordinate frame is along the $\vec{p}_{beam}$ vector, and the x axis completes the right-handed coordinate frame.

The COSY-11 detection setup is an asymmetrical aparatus, hence in the case of the $\vec{p}p \rightarrow pp\eta$ reaction, the acceptance for events where the η meson is produced to the left side with respect to the polarisation plane is far larger as compared to the events where it is emitted to the right. Therefore, the left-right asymmetries are determined from numbers of events with the η meson production to the left side, measured for the spin up and spin down modes of the beam polarisation. Additionally, the acceptance of the COSY-11 facility allows to register only events scattered near the horizontal plane. In the analysis the azimuthal angle ϕ_η was restricted to values of $\cos\phi_\eta$ ranging between 0.87 and 1.

Let us define $N_+^\uparrow(\theta_\eta)$ and $N_-^\downarrow(\theta_\eta)$ as production yields of the η meson emitted to the left around the θ_η angle as measured with the up and down beam polarisation, respectively, i.e.

$$N_+^\uparrow(\theta_\eta) = \sigma_0(\theta_\eta)\left(1 + P^\uparrow A_y(\theta_\eta)\right)E(\theta_\eta)\int L^\uparrow dt, \tag{1}$$

$$N_-^\downarrow(\theta_\eta) = \sigma_0(\theta_\eta)\left(1 - P^\downarrow A_y(\theta_\eta)\right)E(\theta_\eta)\int L^\downarrow dt, \tag{2}$$

with $\sigma_0(\theta_\eta)$ denoting the cross section for the η meson production for unpolarised beam, $P^{\uparrow(\downarrow)}$ standing for the polarisation degree corresponding to spin up and down modes, $\mathrm{E}(\theta_\eta)$ being the efficiency of the COSY-11 facility for detecting the η meson emitted to the left side at the θ_η angle and $L^{\uparrow(\downarrow)}$ denoting the luminosity during the beam polarisation up and down. Signs in the brackets of Eqs. 1 and 2 follow the Madison convention [2].

[2] The detailed derivation of the Eqs. 1 and 2 can be found in [30].

Assuming that $P^{\uparrow} \approx P^{\downarrow}$ [3] and introducing the average beam polarisation $P \approx \frac{P^{\uparrow}+P^{\downarrow}}{2}$, the relative luminosity $L_{rel} = \frac{\int L^{\uparrow} dt}{\int L^{\downarrow} dt}$ and solving Eqs. 1 and 2 for $\mathrm{A}_y(\theta_\eta)$ we obtain:

$$A_y(\theta_\eta) = \frac{1}{P} \frac{N_+^{\uparrow}(\theta_\eta) - L_{rel} N_-^{\downarrow}(\theta_\eta)}{N_+^{\uparrow}(\theta_\eta) + L_{rel} N_-^{\downarrow}(\theta_\eta)}. \quad (3)$$

Therefore in order to calculate the analysing power one has to measure the relative luminosity L_{rel}, the average beam polarisation P, and the production yields $N_+^{\uparrow}(\theta_\eta)$ and $N_-^{\downarrow}(\theta_\eta)$.

Relative luminosity

The relative luminosity for both excess energies has been determined by means of the measurement of coincidence rate in the polarisation plane [30]. Due to parity invariance for strong interactions, the differential cross section for any two-body nuclear reaction in the polarisation plane does not depend on the magnitude of polarisation. Thus, the number of reactions measured in the polarisation plane is proportional to the integrated luminosity over the time of measurement. The ratio of the numbers of events during spin up and down modes were used as a measure of the relative luminosity. Values of $L_{rel}^{10} = 0.98468 \pm 0.00056(stat) \pm 0.00985(sys)$ and $L_{rel}^{36} = 0.98301 \pm 0.00057(stat) \pm 0.00985(sys)$ have been obtained at the excess energies of Q = 10 and 36 MeV, respectively.

Polarisation

The beam polarisation measurements have been performed with three independent detection setups. In the run at the excess energy of Q = 10 MeV the COSY-11 polarimeter has been used [30] as the main equipment to extract the information about the value of the polarisation degree. During this run a cross-check of the method was done by means of the COSY polarimeter [39], and for the measurement at the excess energy of Q = 36 MeV the EDDA detection setup [38] has been exploited.

In all measurements the left-right asymmetry for the $\vec{p}p \to pp$ reaction was determined, and the polarisation was derived using the data base of the analysing powers for the $\vec{p}p \to pp$ reaction, measured by the EDDA collaboration in the wide range of beam momenta and scattering angles [38]. For the detailed description of detector setups used for the polarisation determination the reader is referred to [30]. The values of polarisation degree $P^{10} = 0.680 \pm 0.007(stat) \pm 0.055(sys)$ and $P^{36} = 0.663 \pm 0.003(stat) \pm 0.008(sys)$ have been obtained, for Q = 10 and 36 MeV, respectively.

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[3] Which is valid within ±2% accuracy, as has been studied with the EDDA [38] and COSY [39] polarimeters.

Production rates

The production rates $N_+^\uparrow(\theta_\eta)$ and $N_-^\downarrow(\theta_\eta)$ from Eq. 3 have been extracted from the missing mass spectra. The range of the θ_η angle has been divided into four bins, at both excess energies [30]. The examplatory spectra of the missing mass distributions for the fourth bin as measured with spin up and down orientation at the excess energy of Q = 10 MeV are presented in Fig. 2.

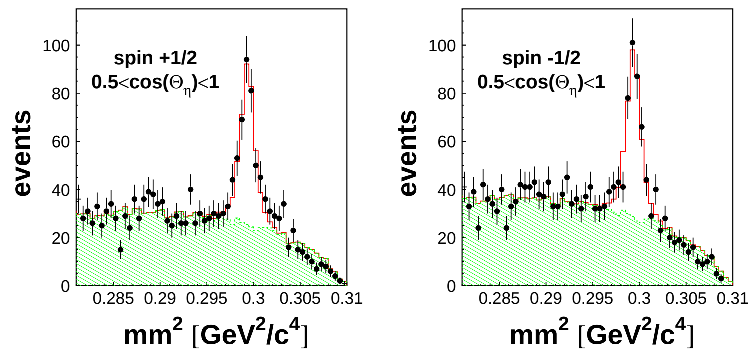

FIGURE 2. Examples of missing mass spectra for $\cos\theta_\eta \in (0.5;1)$ and opposite beam polarisation states, as measured at the excess energy Q = 10 MeV. Full points correspond to the experimental values which are shown with their statistical uncertainties. The solid line represents the sum of the $pp\eta$ and multipion background production channels determined by Monte-Carlo simulations. The shaded parts of the histograms show the simulated contributions from the multipion background.

To separate the actual production rates from the background both the reactions with multipion production as well as the events with the η meson production have been simulated using the program based on the GEANT3 code. A fit of the simulated missing mass spectra to the corresponding experimental histograms has been performed with the amplitudes of the simulated spectra, beam momentum smearing and the deviation of the beam momentum from its nominal value treated as the free parameters. The integral of the Monte-Carlo spectrum yielded the production rates. For more details on the determination of the production rates the reader is referred to [30].

In the case of the measurement at Q = 36 MeV, the η meson peak on the missing mass spectrum was well separated from the kinematical limit and the multipionic background could have been described by a polynomial of second order [30].

RESULTS

The analysing powers for both excess energies have been determined according to the Eq. 3 and are presented along with their statistical errors in Fig. 3. The method of analysis is presented in details in [30], and the results were already published in [40, 41]. Tested predictions of reference [19] were based on the assumption of the ρ meson exchange dominance and the proton asymmetries taken from the photoproduction of the η meson [42]. In the case of the calculations of reference [18] the exchanges of all mesons have been taken into account in the framework of the relativistic meson exchange model

of hadronic interactions and it was found in this model that the contribution from the pion exchange is the dominant one.

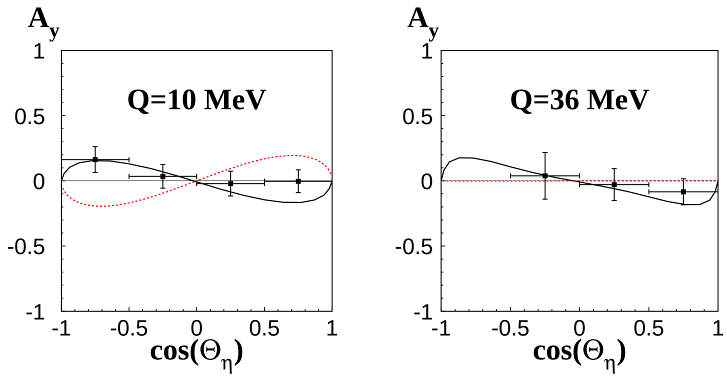

FIGURE 3. Analysing powers for the $\vec{p}p \to pp\eta$ reaction as functions of $\cos\theta_\eta$ for Q = 10 MeV (left panel) and Q = 36 MeV (right panel). Full lines are the predictions based on the pseudoscalar meson exchange model [18] whereas the dotted lines represent the calculations based on the vector meson exchange [19]. In the right panel the dotted line is consistent with zero. Shown are the statistical uncertainties solely.

The χ^2 tests of the correctness of the models based on the dominance of the ρ [19] and π [18] meson exchanges have been performed. The reduced value of the χ^2 for the pseudoscalar meson exchange model was determined to be $\chi^2_{psc} = 0.54$, which corresponds to a significance level $\alpha_{psc} = 0.81$, whereas for the vector meson exchange model $\chi^2_{vec} = 2.76$, resulting in a significance level of $\alpha_{vec} = 0.006$.

In the vector meson exchange dominance model [19] the angular distribution of the analysing power is parameterized with the following equation:

$$A_y(\theta_\eta) = A_y^{max,vec} \sin 2\theta_\eta, \tag{4}$$

where the amplitude $A_y^{max,vec}$ is a function of the excess energy Q, shown as a dotted line in the left panel of Fig. 4.

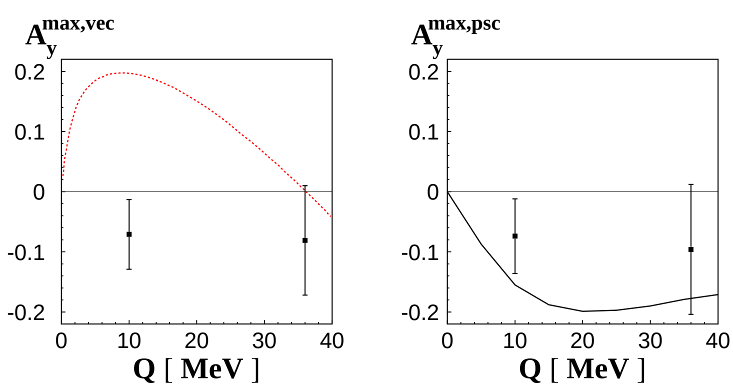

FIGURE 4. Theoretical predictions for the amplitudes of the analysing power's energy dependence confronted with the amplitudes determined in the experiments at Q = 10 and Q = 36 MeV for the vector (left panel) and pseudoscalar (right panel) meson exchange dominance model.

We have estimated the values of $\mathrm{A}_y^{max,vec}$ comparing the experimental data with predicted shape utilizing a χ^2 test. The values of $\mathrm{A}_y^{max,vec}$ for Q = 10 and 36 MeV have been determined to be $\mathrm{A}_y^{max,vec}(Q=10) = -0.071 \pm 0.058$ and $\mathrm{A}_y^{max,vec}(Q=36) = -0.081 \pm 0.091$, respectively. Similar calculations have been performed for the pseudoscalar meson exchange model [18], assuming that the shape of the analysing power as a function of the $\cos\theta_\eta$ does not depend on the excess energy, which is correct within about 5% accuracy. It has been found that $\mathrm{A}_y^{max,psc}(Q=10) = -0.074 \pm 0.062$, and $\mathrm{A}_y^{max,psc}(Q=36) = -0.096 \pm 0.108$. These results are shown in Fig. 4. The figure shows that the predictions of the model based on the π mesons dominance are fairly consistent with the data, whereas the calculations based on the dominance of the ρ meson exchange differ from the data by more than four standard deviations. However, the latter calculation used the proton asymmetry (T) in eta photoproduction [42], within the framework of the vector meson dominance model [43], as the basis of their estimate. It should be noted that it has proved hard to reconcile the experimental value of T with the results of photoproduction amplitude analyses [44].

CONCLUSIONS AND OUTLOOK

Taking into account the χ^2 analysis of the analysing power for the pseudoscalar and vector meson exchange models we have shown that the predictions of the pseudoscalar meson exchange dominance [18] are in line with the experimental data at the significance level of 0.81. On the other hand, the assumption that the η meson is produced solely via the exchange of the ρ meson [19], leads to the discrepancy between the theoretical predictions and experimental data larger than four standard deviations. It must be stated, however, that the production amplitude for the ρ meson exchange was determined based on the vector meson dominance hypothesis and the photoproduction data [42]. At this point it is also worth mentioning that the recent calculations of the η meson production in the NN collisions performed in the framework of the effective Lagrangian model [45] also indicate the dominance of the pion exchange.

The analysing power values for both excess energies are consistent with zero within one standard deviation. This is in line with the results obtained by the DISTO [29] collaboration in the far-from-threshold energy region. Such a result may indicate that the η meson is predominantly produced in the *s*-wave.

The improvement of the statistics would be possible with the measurements performed at the WASA-at-COSY facility [46]. Thanks to instalation of a pellet target, high luminosities for the experiments with polarised proton beams are expected, promising to achieve the production yield of around 20000 η mesons per day measured at the excess energy of Q = 10 MeV. An experiment with such a high production rate within one weak would enable to reduce the error bars presented in Fig. 3 by factor of 7. The letter of intent for such an experiment has already been prepared by the COSY-11 collaboration. For more details see [47].

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